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14. ABSTRACT

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Applications of Uncertainty in Environmental Acoustic Characterization

28 September 2007

John Zittel

SAIC – Advanced Sensors & Analysis Division

Prepared for:

Dr. John Tague

ONR 321US

Under contract #: N00014-00-D-0103/0013

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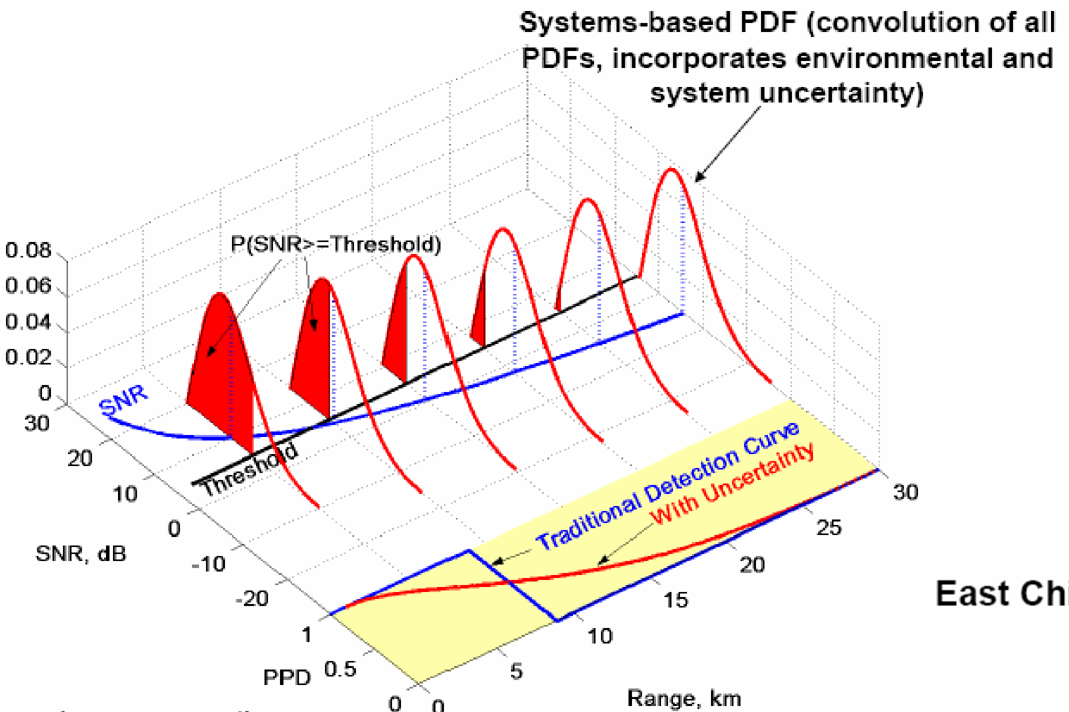
Background

- ONR’s ‘Capturing Uncertainty’ DRI culminated with a set of ‘Navy Day’ presentations in January 2005
- Technologies presented are applicable to:
  - Area characterization of variability (spatial and temporal) for both preparation of the battle space and real-time operations
  - Improved modeling of and tactical guidance for USW systems
  - Improvements in system performance by adapting to variable conditions
- This paper is intended to discuss opportunities to further mature, demonstrate or transition these capabilities

Outline

- A sampler of key results from ONR Uncertainty DRI
- Transition targets
- Implications and possibilities

Probabilistic Performance Prediction Method



μ: mean terms in sonar equation
σ: set by fluctuations of each term
n: local slope of the TL~ R^n

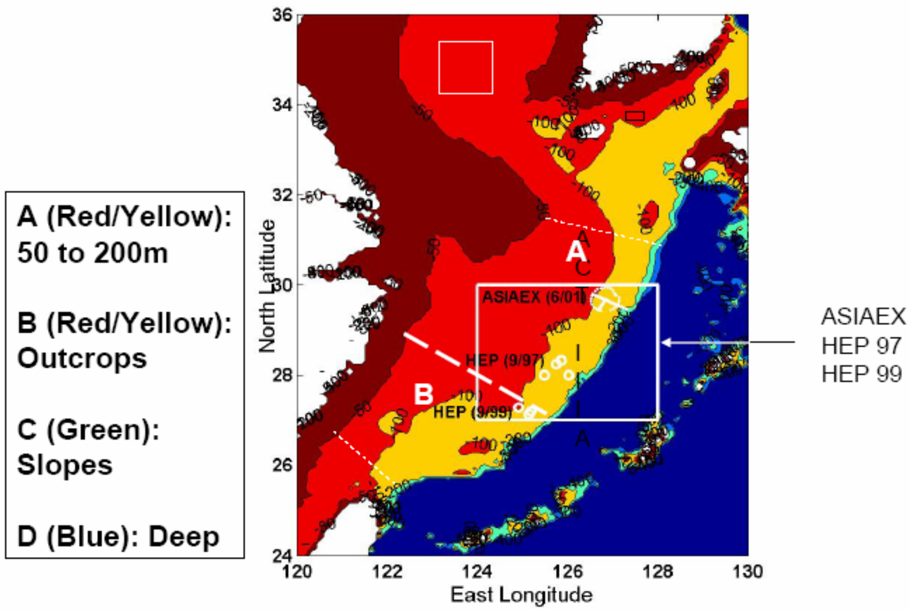
Abbot

Submarine Transmission Loss Vehicle (STLV):
A Submarine-Launched, Mobile, Calibrated Source

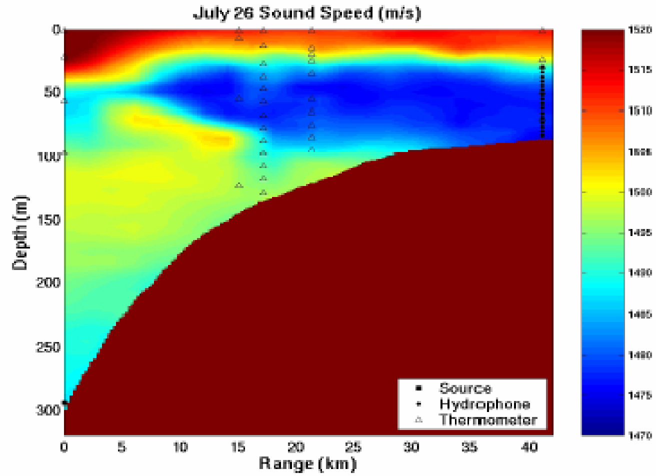
Leverages Sippican's SUBMATT Technology:

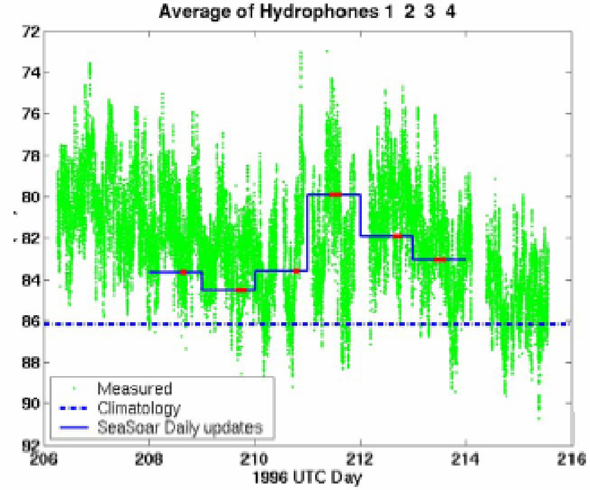
- **Size:** 25 lbs, 44" Length, 4.9" Diameter
- **Depth:** 75 - 600 ft (± 25 ft)
- **Programmable** Run Geometry
- **Launched** from Submarine Trash Disposal Unit
- **Dynamics:** Speed 3 - 6 kts
- **Battery Power:** Alkaline
- **Endurance:** 2-6 Hrs

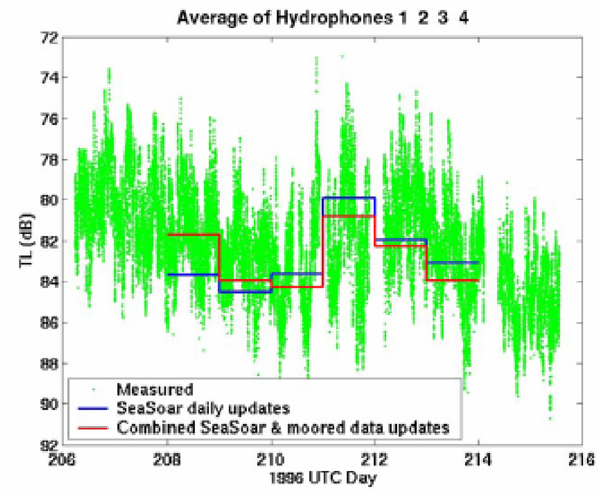
East China Seas TL Provinces for Performance Prediction (Preliminary)



Chiu







Summary of Findings

SCS Shelfbreak TL Uncertainty (Short-scale) Characterization:

•Knowing whether the nonlinear internal waves are "present" or "absent" and the amplitude of the lead wave is key to assigning the proper uncertainty statistics.

•Both nonlinear internal waves and bottom contribute significantly, and almost equally, to the observed σ_{TL}^2.

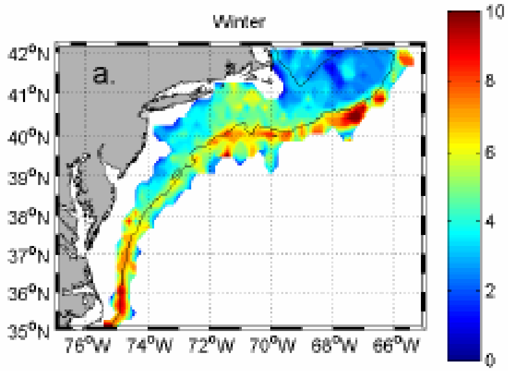
•σ_{TL}^2 also depends strongly on the multipath arrival structure and the bandwidth (or pulse width) of the transmitted signal.

TL Uncertainty (long scales) Reduction:

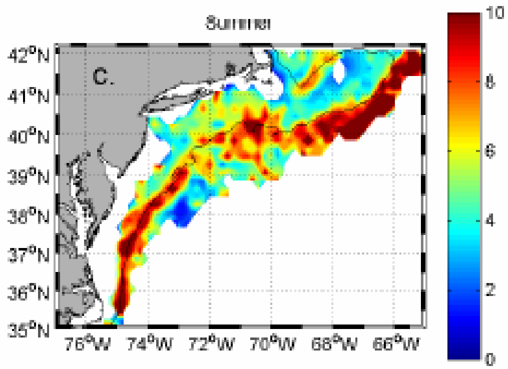
•Data integration/assimilation can reduce uncertainty in the daily mean TL.

•Daily mean TL estimate is somewhat sensitive to the resolution the sound speed field.

Uncertainty Map- Mid-depth Soundspeed St. Dev.



Winter planview

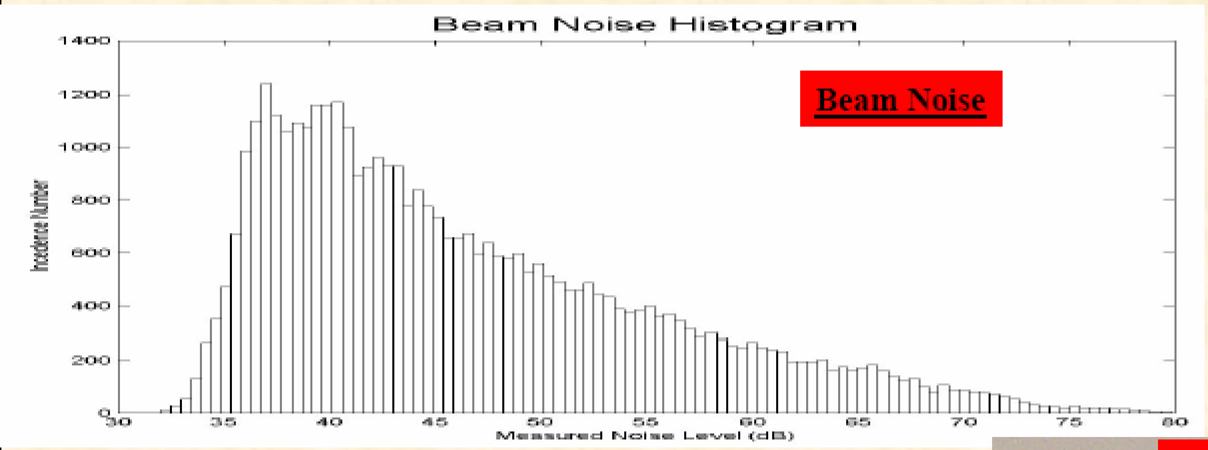


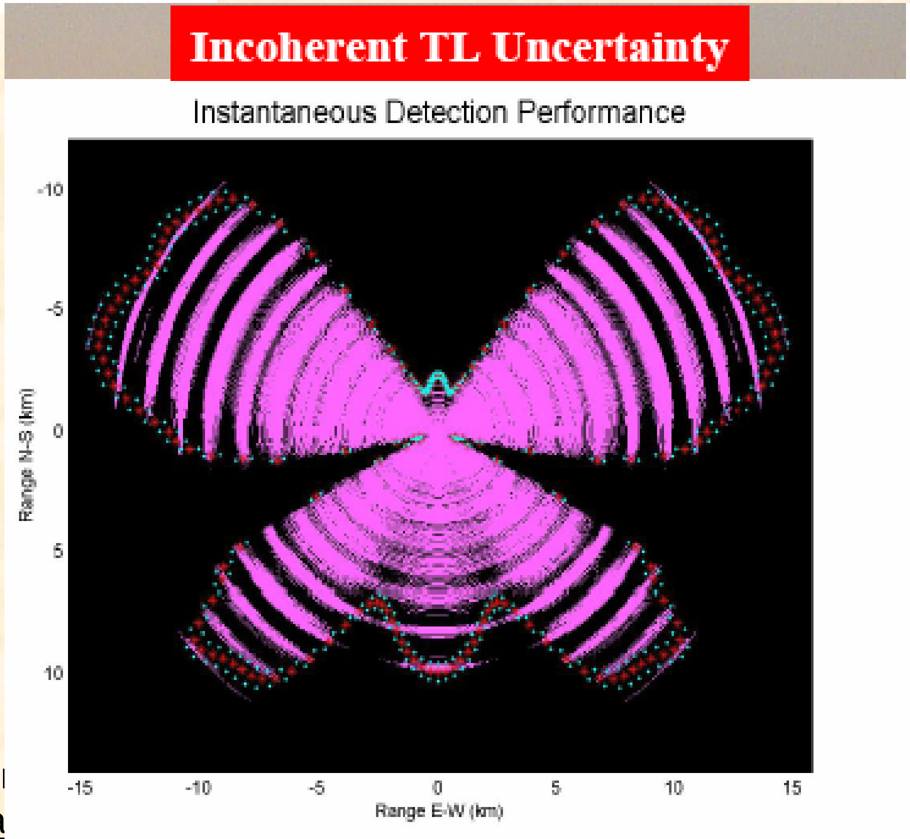
Summer planview

Conclusions

- Climatologies of Soundspeed Standard Deviations can identify regional "hotspots" correlated with known ocean features
- Allows direct comparison of seasonal differences including vertical position of St. Dev. Maximum and cross-shelf scale of maximum
- Structure of climatological fields can also be cross-compared with intensive surveys over limited time frames (e.g. subsurface maximum in summer confirmed in high-resolution experiment)

Heaney





- Measure what you can
- Model what you must
- Display uncertainty

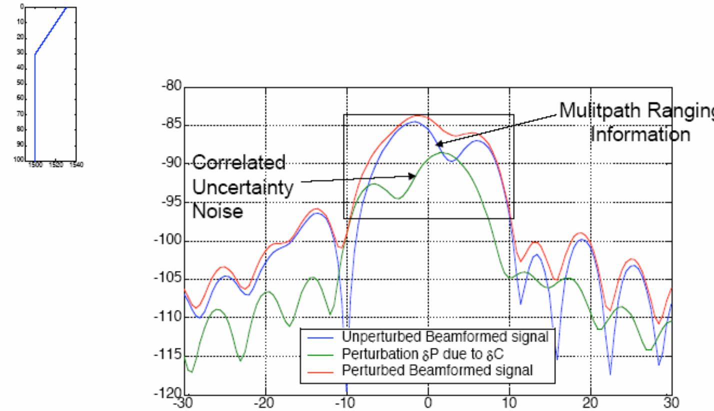
What/Why the Adjoint Method?

- Determine which spatial regions cause largest uncertainty in observations and/or system performance
- But--Parameter Space (environmental uncertainty) much larger than Observation Space (sensors)
- Procedure based on sensor number, not environmental parameters(~infinite)
- Efficiently calculate a Sensitivity Map

Kuperman

Example: 20 element, 50 m offboard v. array (300 Hz)

Summer – Source @ 30m

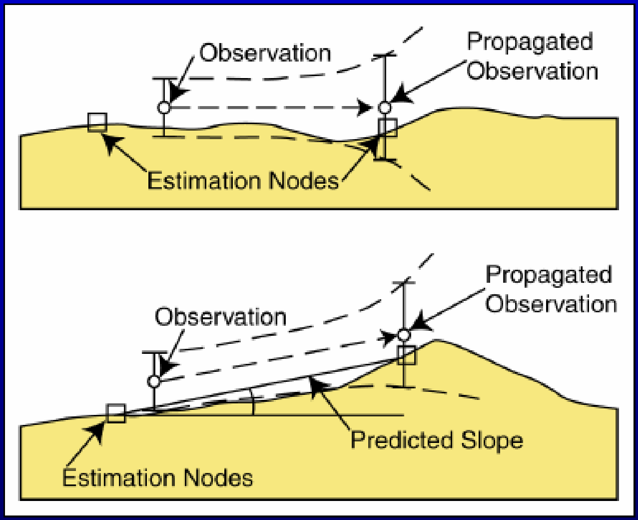


Summary

- Sensitivity Matrix provides efficient characterization of uncertainty
- Procedure uses existing acoustic models
- Can be applied to system performance prediction
- Next
  - Apply to more conventional sonar systems, towed arrays, offboard sensors, multistatic systems, etc
  - Develop specific algorithms using existing performance prediction models;
  - Develop optimum sensor deployment procedure to minimize impact of environmental uncertainty
  - Develop robust beamformers insensitive to Uncertainty
  - Time dependent oceanographic inversions

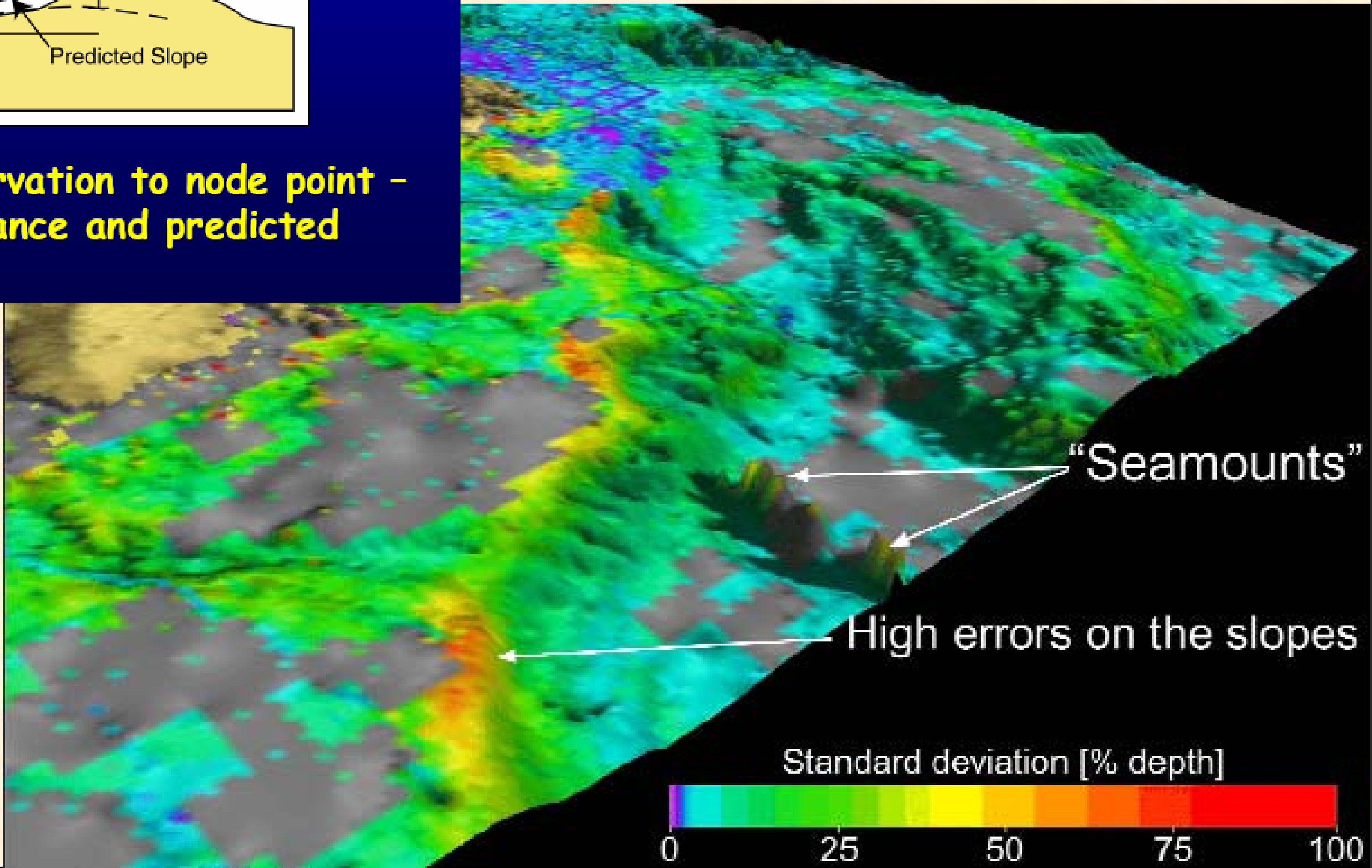
28 Sept 2007

Estimate & Uncertainty Propagation



- **Propagate observation to node point – weighted by distance and predicted performance**

Mayer



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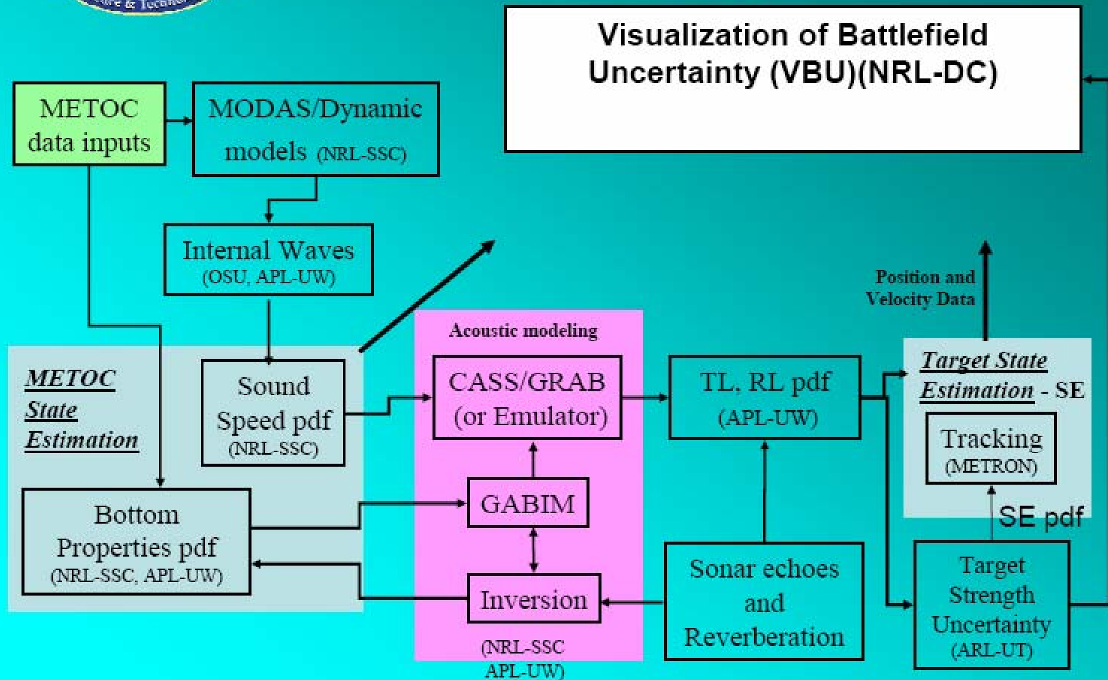
Technical Approach



Miyamoto

Summary

- Developed new capability for improved tactical performance from a multi-static active field that takes into account sensor performance prediction.
  - And, is robust to uncertainty
- Developed new methodologies for the characterization of the environment and the propagation of that uncertainty through an acoustic model.
- Demonstrated performance gains with simulated and operational (albeit structured) data sets

ASWIP efforts

- FEB04 ASWIP
  - Need for uncertainty quantification not on record as a METOC WG issue
  - Need for environmental uncertainty & variability estimates discussed in the METOC WG
    - ✓ Ellen Livingston brief
      - "Capturing Uncertainty Initiative"
    - ✓ Phil Abbot brief
      - "Predictive Probability of Detection for Tactical Sonar Systems"
  - Uncertainty issue part of METOC WG minutes, but not presented to ESC during outbrief
- AUG04 ASWIP
  - Need for uncertainty/variability metrics seen as necessary by all METOC Sub-WG leads in order to "Reinvigorate Navy Oceanography"
    - ✓ CAPT Paul Heim (C2F) – Fleet Support & CONOPS Sub-WG
    - ✓ LCDR Pat Cross (CSP) – Sensing Strategy Sub-WG
    - ✓ Mr. Kim Koehler (PMW 180) – R&D/S&T Sub-WG
  - Uncertainty issue touched on during ESC outbrief
    - ✓ "Address the Metrics…"
- Recommendation to CAPT Petzrick
  - Address uncertainty initiatives to ESC as a METOC top priority at Winter 05 ASWIP

Applications

- Technologies presented are applicable to:
  - Area characterization of variability (spatial and temporal) for both preparation of the battle-space and real-time operations
  - Improved modeling of and tactical guidance for Undersea Warfare systems
  - Improvements in system performance by adapting to variable conditions

Area Characterization – Spatial and Temporal

- Supports
  - Preparation of the battlespace
  - Real-time operations
  - SPL extraction
- Approaches
  - Environmental sampling
    - Geoacoustic inversion is a key example
    - Water column characterization is also critical in some locations
  - Use of climatological models to identify regional ‘hot spots’
    - For operational use (e.g., buoyancy control)
    - As input to variability estimates (qualitative or quantitative) in near-term modeling improvement
    - To motivate sampling strategies

Geoacoustic Inversion

- Applicable to:
  - SPL extraction
  - Performance prediction
  - Battle space preparation
- Sound source opportunities
  - Target signature itself
  - Ship(s) of opportunity
  - Expendable source (OASIS, ARL:UT, U Miami have all at various times proposed)
- Approaches
  - ARL:UT (Knobles)
  - OASIS (Heaney)
  - Numerous others – see e.g.,
    - Special issue on "Geo-acoustic Inversion in Range-dependent Shallow-water Environments", IEEE J. Oceanic Engineering, 28 (3), July 2003
    - King, D., et. al., "Recommendations for the Geoacoustic Inversion Toolkit (GAIT), NRL/MR/7140—06-8938, 31 March 2006

Water Column Characterization

- With gliders / autonomous vehicles
- Issues include
  - Sampling strategies
    - Track selection
    - Identification of key locations for sampling
  - Parameter selection
    - Temperature
    - Salinity
    - Ambient noise
    - …
  - Data ingestion strategies for strings of data into MODAS
  - Demonstration of value-added

Improvements to Sonar Performance Prediction

- Very near term
  - Inject measurements when possible (Heaney, Chiu)
  - Apply warnings where needed
- Near term
  - Identify bias and variance in predictions
  - Provincing and identification of dominant effects
- Mid term
  - Explore more sophisticated tools to manage variability (e.g., Kuperman – adjoint method)
  - Utilize tools for visualization of uncertainty (Mayer)
- Long term
  - Stochastic methods (e.g., Abbot et. al.)

Improvements in System Performance

- Use improved TDAs to improve positioning and operation of sensors
- Use awareness of uncertainty to adaptively determine and modify detection threshold
  - Applied to EER (Miyamoto et al)
  - Could also be applicable to passive towed and distributed sensors
- Use adjoint method (Kuperman et al) in adaptive beamforming

Transition Targets

- Area characterization of variability
- Improved modeling of and tactical guidance for USW systems

- CNMOC is central
- Some tools require a close link with SYSCOMs

- Improvements in system performance by adapting to variable conditions

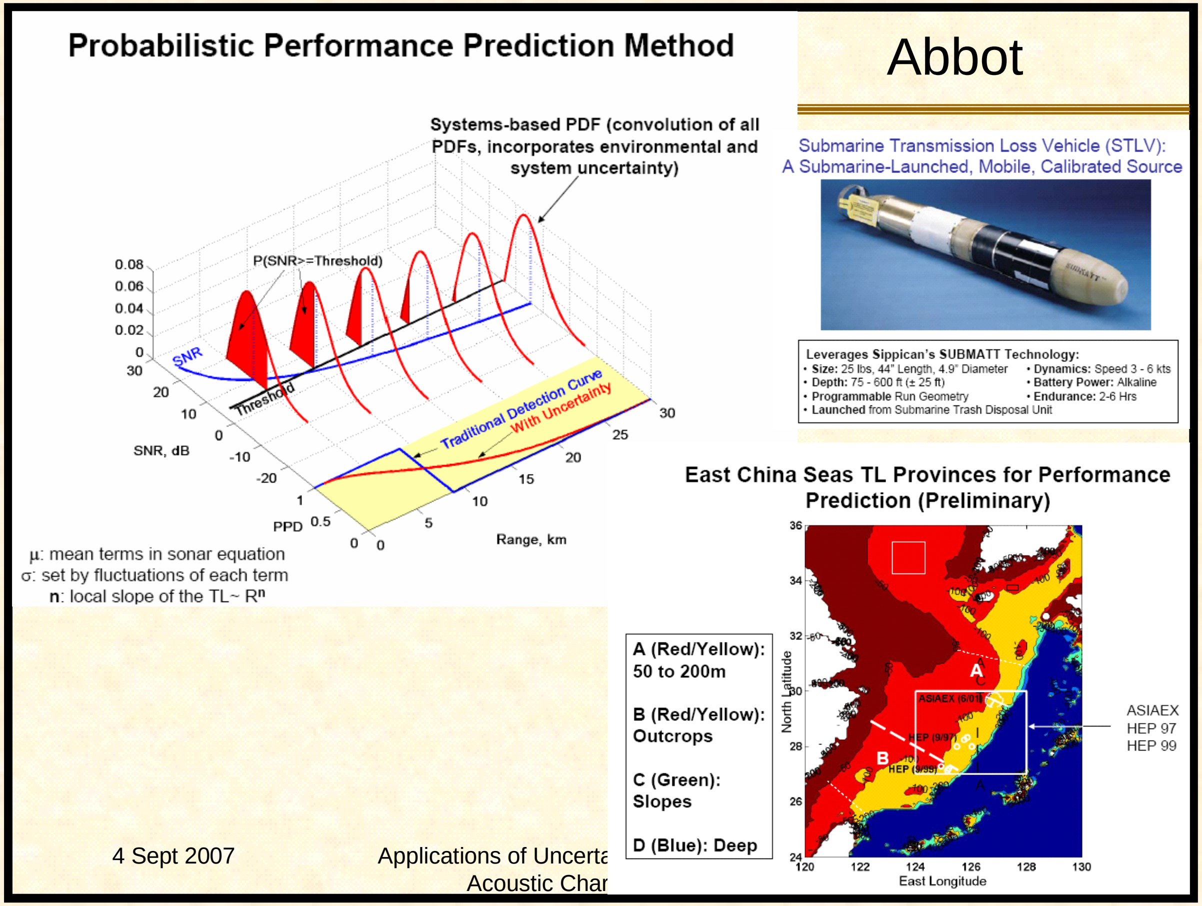
- Focus on discrete systems

Following will discuss:

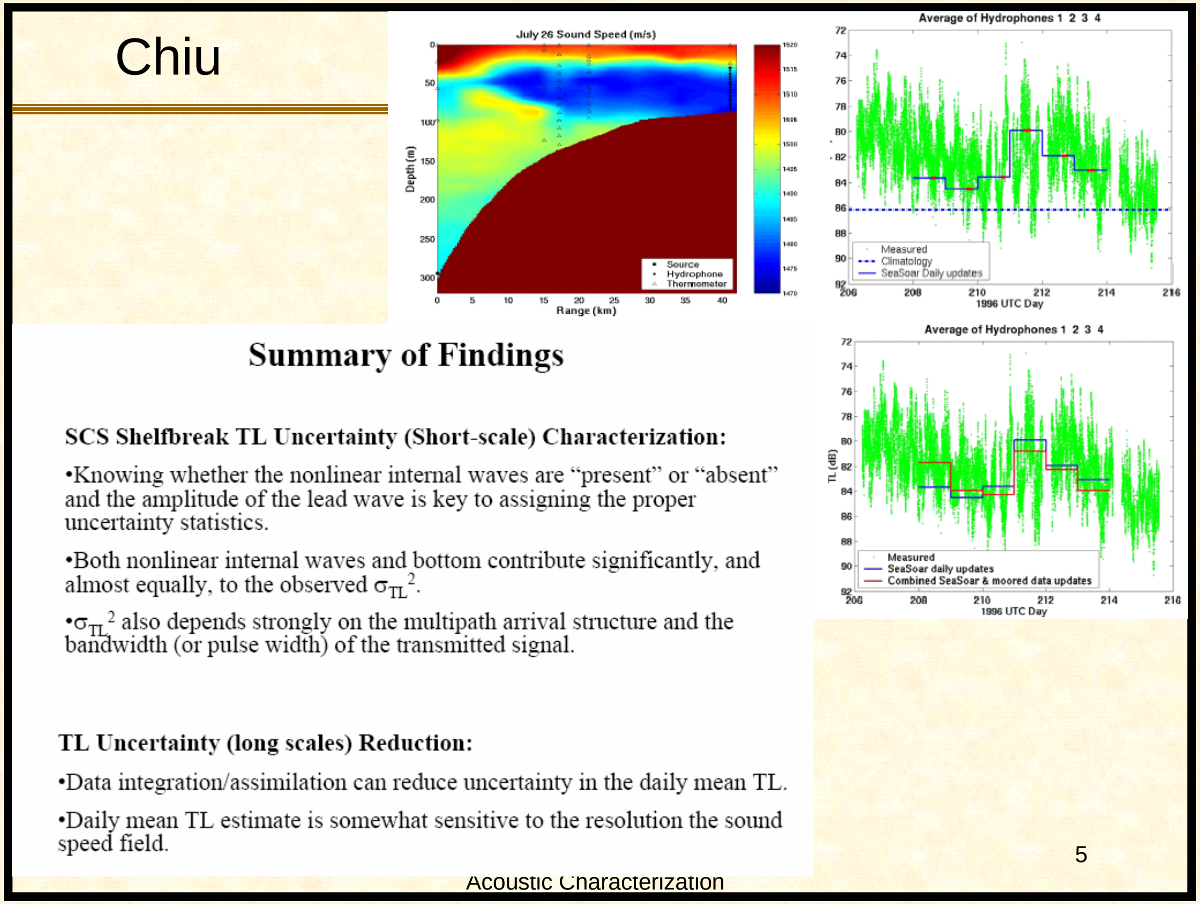
- Approaches to, status of and opportunities for transition
- Approaches to fostering transition and monitoring success

Considerations for Transition

- CNMOC is the natural focal point for many of these technologies
  - Some directly support CNMOC products
  - Others enhance CNMOC support to SYSCOM developers
- Need a multi-time frame perspective
  - Short term vs. long term
  - Varied levels of maturity
- Incremental transition may be a better strategy than a ‘global’ demonstration and transition



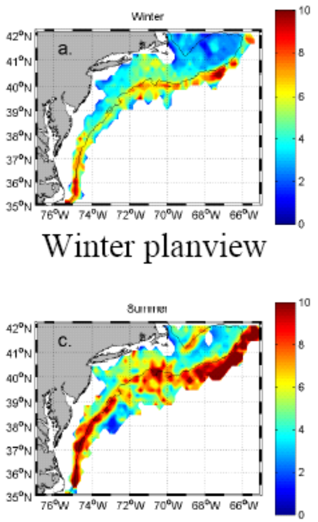
- Status:
  - ✓ Probabilistic methodology in use and being extended
  - – No routine use yet of *in situ* TL measurement
    - Applicability to area characterization and SPL extraction



- Status:
  - Engaged in technology discussions with CNMOC

Gawarkiewicz

Uncertainty Map- Mid-depth Soundspeed St. Dev.



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Summer planview

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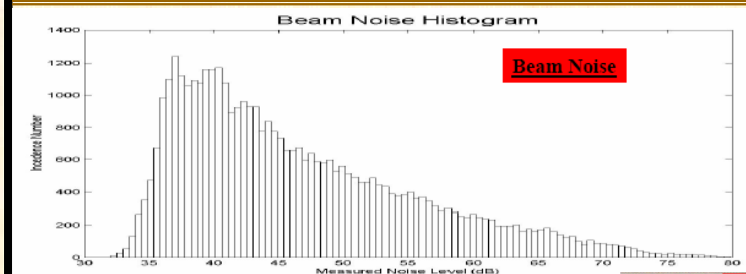
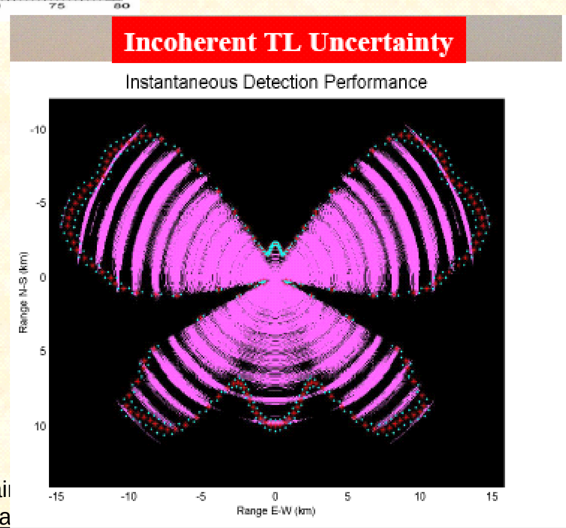
4 Sept 2007 Applications of Uncertainty - Environmental Acoustic Characterization 6

- Status:
  - Engaged in technology discussions with CNMOC

Heaney

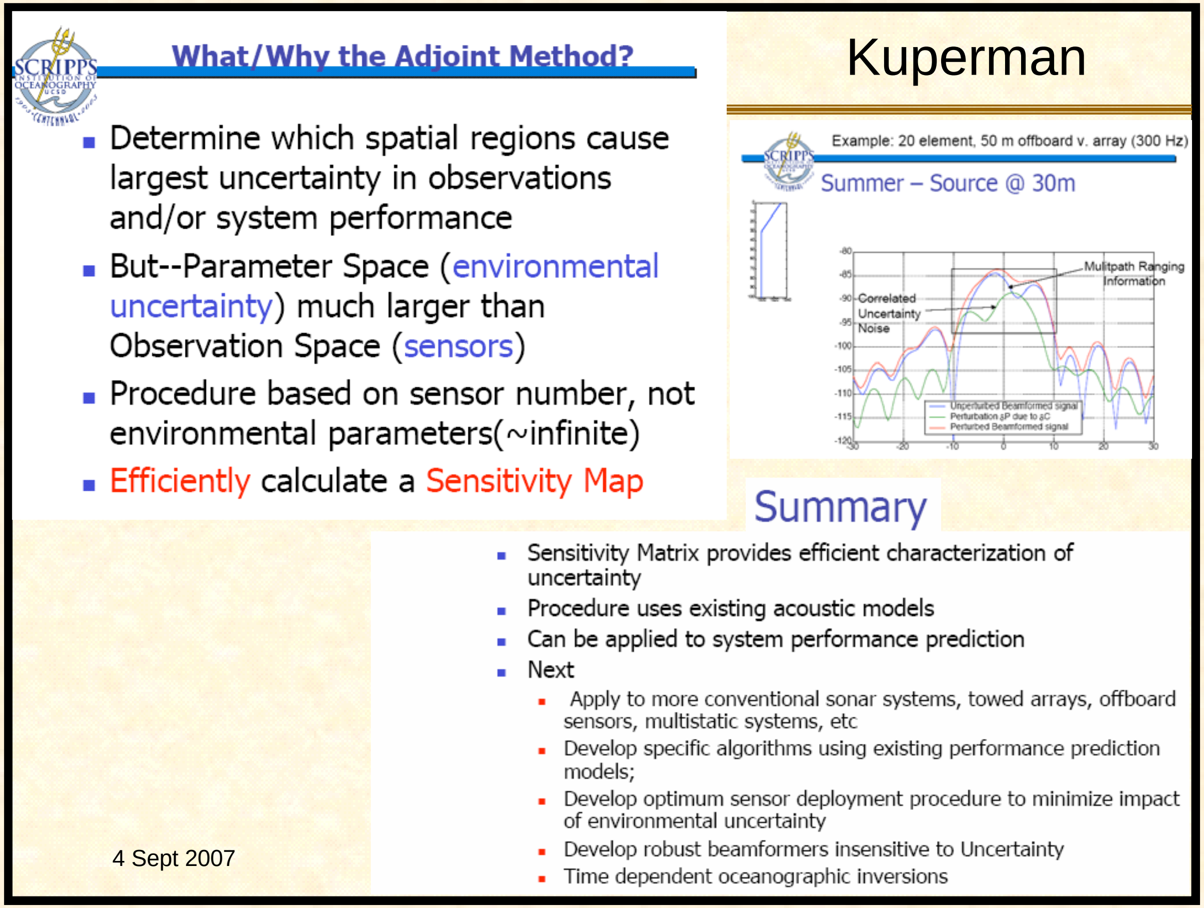




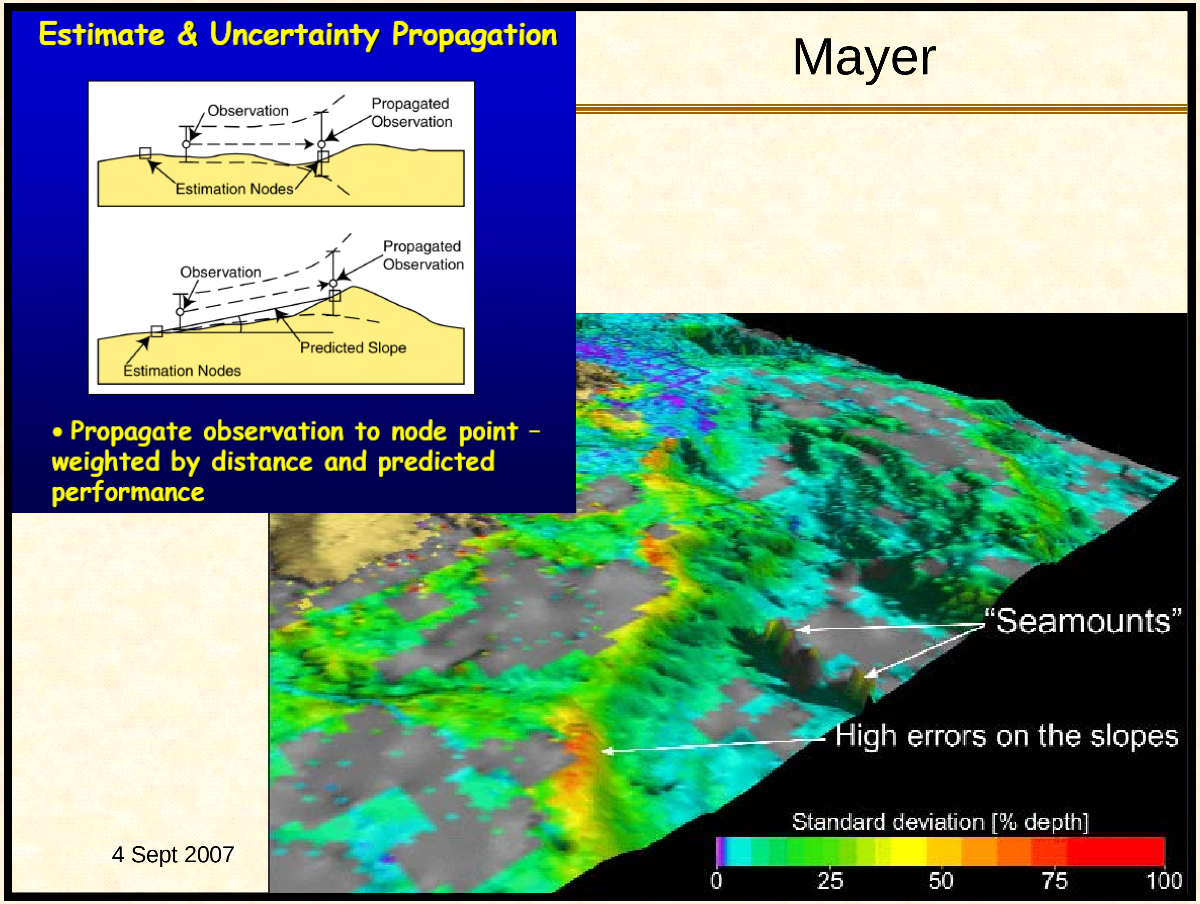
- Measure what you can
- Model what you must
- Display uncertainty

4 Sept 2007 Applications of Uncertai[...] Acoustic Chara[...]

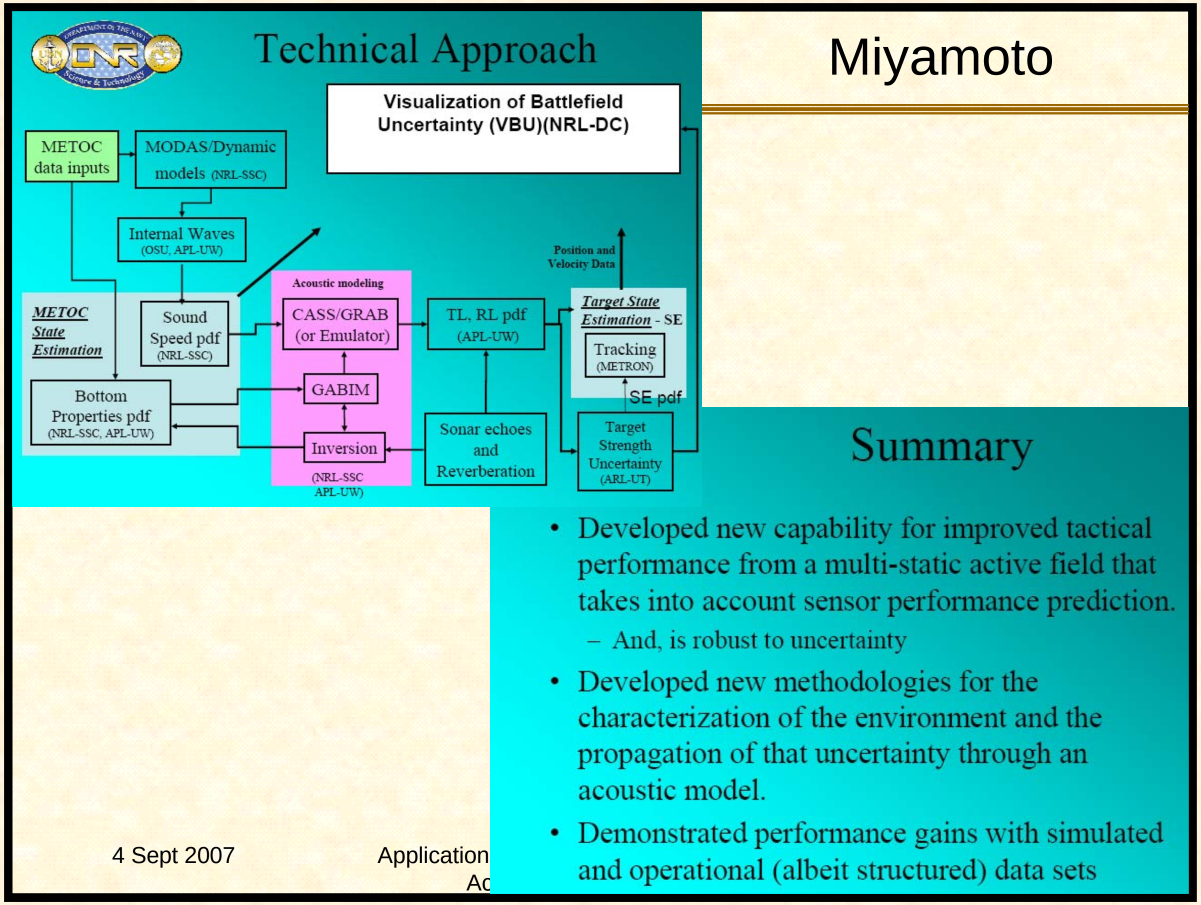
- Status:
  - Represents a philosophy more than a product
  - Use of measurements (e.g., beam noise) affects CNMOC and SYSCOM model developers



- Status:
  - Longer term approach
  - Needs further development, communication and demonstration of utility
  - Possible APB-like product (improved beamforming)



- Status:
  - Awareness exists at CNMOC
  - Longer term approach
    - Direct applicability unclear
  - Needs further communication and demonstration of utility



- Status:
  - Most applicable to systems developers
    - Facing ‘transition gap’ – who funds final demo prior to transition?
  - Invited to visit CNMOC
    - Ultimate use would require SYSCOM and CNMOC partnership

ASWIP efforts

Speckhahn

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  - Uncertainty issue touched on during ESC outbrief
    - ✓ "Address the Metrics…"
- Recommendation to CAPT Petzrick
  - Address uncertainty initiatives to ESC as a METOC top priority at Winter 05 ASWIP

11

- Status:
  - No longer a stand-alone METOC group at the ASWIP
  - Appears no longer to be identified as a stand-alone ASWIP issue
    - Integrated into CNMOC efforts as discussed elsewhere

Managing Variability in TL

- CNMOC is moving down this road
- Valiant Shield was a major milestone
  - Implicitly did a lot of 6.2 development
  - Conducted a Military Utility Assessment
  - Required an unsustainable level of effort
  - Need help with 6.3!

Address Variability and Uncertainty

- Sampling strategies should be designed to assess variability
  - Characterization of PDFs remains a highly empirical process
- Even if these are utilized, there will still remain a shortfall
  - Results are only as good as the underlying inputs
  - Some inputs may be for practical purposes unknowable
- Analytic characterizations of fluctuation behavior may offer advantages in consistent management of variability
  - Some experimental and theoretical work support continued use of phase random hypothesis
  - In other cases, real world variability appears more complex
- Phenomenological modeling may offer insight into locations of concern, e.g., internal waves

Estimate variance as a measure of confidence

Putting the TL Pieces Together

- Tools are at hand: GDEM, LFBL, modeling engines, sampling strategies, analytic statistical characterizations, phenomenological (e.g., water mass dynamics) modeling, interpretive skills
- Disparate activities like bottom characterization (e.g., LFBL) and water column characterization (e.g., GDEM) would be usefully augmented by an umbrella effort to evaluate overall ability to characterize TL
  - Provide measures of confidence, e.g., bias and variance
  - Assess sensitivity to inputs
  - Offer insight into local acoustics, e.g., cross-slope vs down-slope TL
  - Provide insight into underlying data quality

Capturing Variability in Sonar Performance Assessment

- In the near term, sonar equation formulations should be enhanced
  - Improve estimates of mean signal excess
  - Provide measures of confidence
    - Bias and variance
  - Offer measures of sensitivity
  - Offer insight into local acoustics
    - E.g., local shipping behavior; cross-slope vs down-slope TL, IW effects
- In the longer term, stochastic treatments may offer advantages
  - Implicitly and consistently capture variability
  - Tactical oceanography interpretation should guide their evolution
    - What forms of variability are deterministic (e.g., site to site, knowledge of threat) and which are stochastic?
    - How can *in situ* measures be used to reduce variability?

The 6.3 Gap

- Valiant Shield demonstrated a number of new capabilities in a labor intense way
  - Gough (CNMOC TD) describes it as a ‘catastrophic success’!
    - How can it be sustained?
- A strategy is needed to engineer those capabilities into a computer
  - Develop an engineered, reliable operational capability
  - Base on successes to date

Managing Uncertainty

- What were the measures of success in Valiant Shield?
  - It looked great, and made decision makers feel better informed, but:
    Was it giving correct answers?

Three strategies for approaching:

Information theoretic measures of the uncertainty in field quantities (e.g., Shannon entropy)

Correctness of underlying physics in field quantities (oceanographic, e.g., temperature, or acoustic, e.g., TL)

Significance of changes in field (i.e., is the difference between one field and the next signal or noise?)

A separate question is implications for military utility: *Did it improve military performance in quantifiable ways?*

Managing Uncertainty

- Should ONR partner with CNMOC in an umbrella effort to define measures of success and characterize how well we are doing?
  - Is APB a model here?

Information theoretic measures of the uncertainty in field quantities (e.g., Shannon entropy)

Untapped and potentially fertile. Can it make statements not only about uncertainty but also about resolution requirements (i.e., data compression)?

Correctness of underlying physics in field quantities (oceanographic, e.g., temperature, or acoustic, e.g., TL)

The dominant question to date, largely by virtue of continuing interests of acoustic researchers

Significance of changes in field (i.e., is the difference between one field and the next signal or noise?)

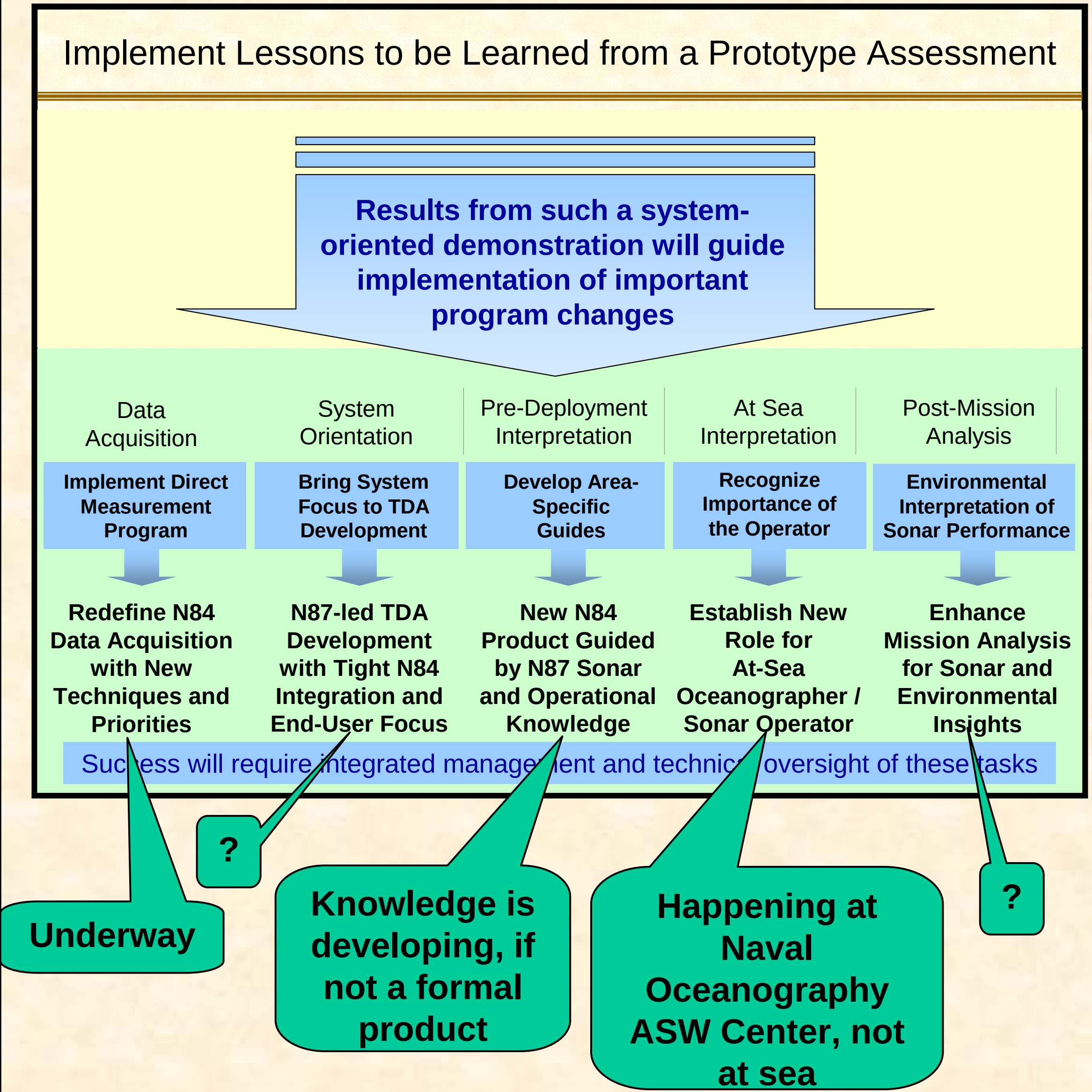
Critical practical question with no clear solution

Managing Uncertainty

Correctness of underlying physics in field quantities (oceanographic, e.g., temperature, or acoustic, e.g., TL)

- Focus on TL, both because of it's importance as a dominant term of the sonar equation, and because it is a proxy for other terms (e.g., noise)
  - But don't ignore other terms
- Can coupled ocean and acoustic data assimilative models improve TL estimates? (Chiu)
- How can uncertainty be cast in operational terms as an ASWIP issue? (Speckhahn)
- A mix of scientific data sets, ocean water mass modeling and geomorphology could be used to test existing data bases and to motivate a 'test case'

What is the Vision?



- This (now dated) vision was prepared in support of the Uncertainty DRI
- The work at CNMOC is consistent with portions of it
- CNMOC and the Naval Oceanography ASW Center have begun forming their own vision
  - Better understanding would help guide everyone

Recommendations

- Transitions to CNMOC
- Continue maturation where appropriate
- Manage remaining uncertainty and measure progress
- Build ONR / CNMOC / SYSCOM links

Transitions to CNMOC

- Support ‘sabbaticals’ at CNMOC
  - Sit side-by-side with team at the Naval Oceanography ASW Center
    - See what they are doing, learn their problems, offer possible solutions
    - Listening is more important than talking at this stage!
- ONR program managers visit CNMOC
  - Need to see the Naval Oceanography ASW Center
  - 321US visit CUS also
- CNMOC leadership provide requirements inputs to ONR
- Any experiment(s) should be in the context of CNMOC activities
  - Insertion of discrete capabilities into the Naval Oceanography ASW Center ‘baseline’
    - Perhaps as a result of sabbaticals
  - Not a stand-alone ONR ‘demonstration’
  - Opportunities for experimentation include:
    - RIMPAC 08
      - Summer, Hawaii Op Area
    - Something similar to Valiant Shield will occur again in 09 and in future years

Continue Maturation Where Appropriate

- Other interests at CNMOC include:
  - Visualization (Mayer)
  - Adjoint methods (Kuperman)
  - Improvements in system performance by adapting to variable conditions (Miyamoto)
- Still need to establish relevance and utility to CNMOC

Manage Remaining Uncertainty and Measure Progress

- At the system level, characterizing and managing uncertainty remains an important issue worthy of S&T investment
- At least three strategies, of varying maturity, suggest themselves:
  - Information theoretic approaches
  - Correctness of underlying physics in field quantities
  - Significance of changes in field
- As ONR fosters transition of these technologies, it should also work with users to define measures of success
  - Is APB a model here?

Build ONR / CNMOC / SYSCOM Links?

- Some technologies need a marriage between CNMOC and SYSCOMs, e.g.,
  - Improved tactical performance based on sensor performance prediction (Miyamoto)
  - Injection of [beam noise] measurements into model predictions (Heaney)
- These approaches by their nature imply a partnership between CNMOC and the SYSCOM developers
  - How can that partnership be nurtured?
- Is there an ONR role?

Conclusion

- Uncertainty DRI is clearly a success story
  - More than I had realized!
  - Some products are in direct use by CNMOC
    - Others have informed CNMOC development work
- Further support of transition to CNMOC would be helpful
  - Improve communications (sabbaticals, program manager visits, …)
  - Insert discrete technologies into CNMOC experimentation
  - Targeted investment in maturation
  - Help is needed with the 6.3 gap
  - Manage remaining uncertainty and measure effectiveness
- Some technologies marry space-time processing with environmental acoustics
  - Exploitation requires a strengthened CNMOC / SYSCOM link
  - Is there an ONR role in fostering?